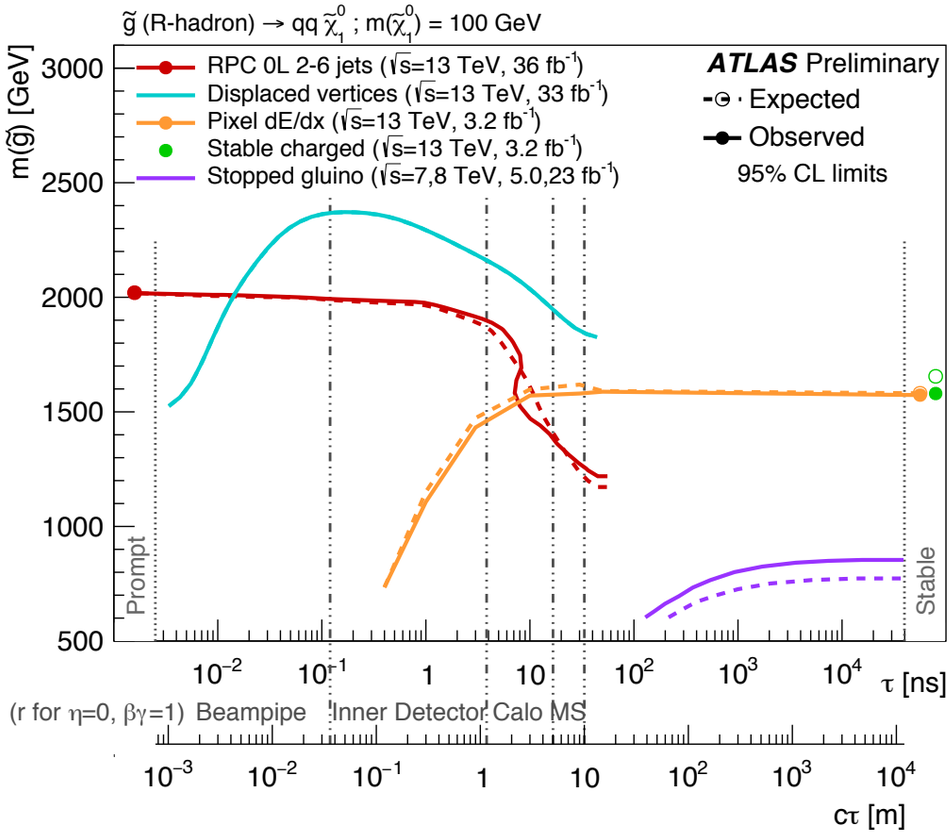
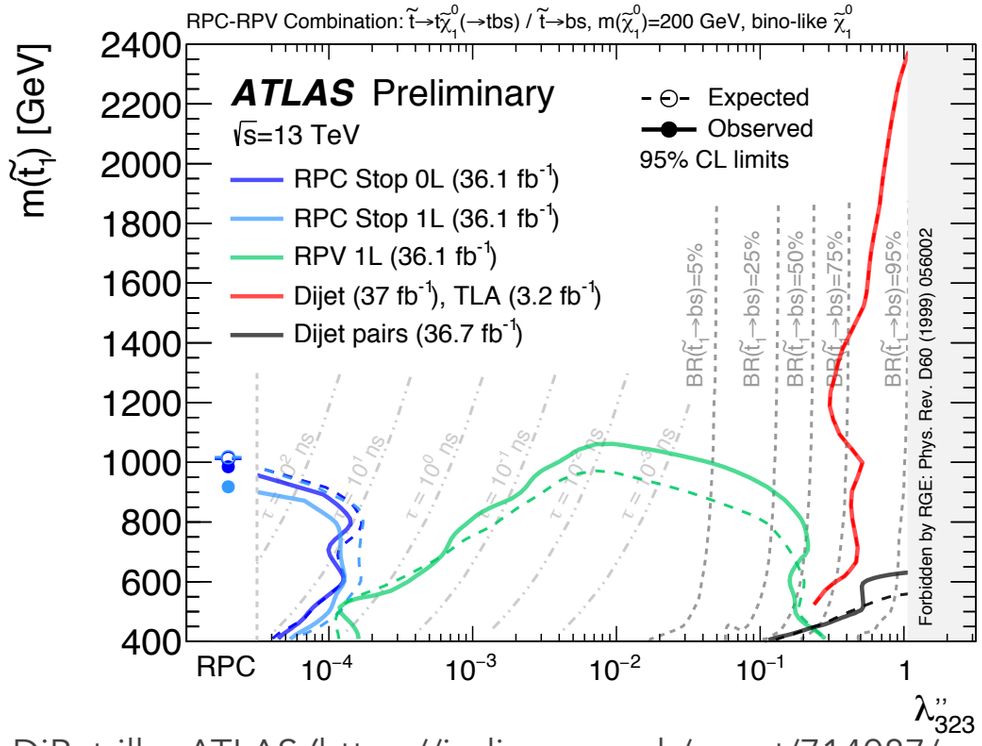
BENCHMARKS FOR LONG-LIVED PARTICLE SEARCHES





talk by K. DiPetrillo, ATLAS (https://indico.cern.ch/event/714087/contributions/3007780/attachments/1652429/2643515/2018.05.18.kdp.RPCmeetsRPV.pdf)

Brian Shuve

July 21, 2020

Snowmass Energy Frontier Workshop

HARVEY MUDD COLLEGE

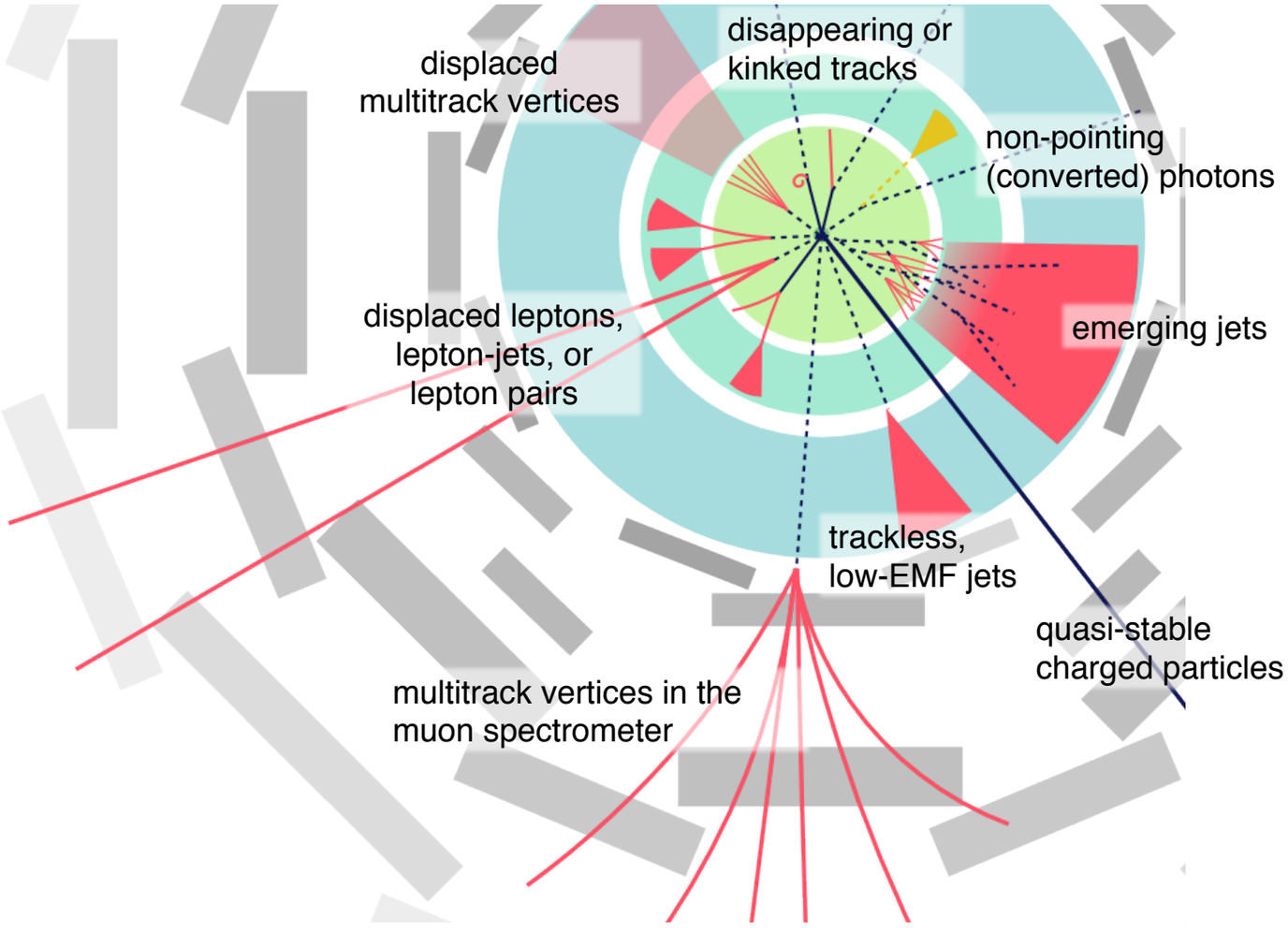
LONG-LIVED PARTICLES

- Rich array of signatures

- Excellent discovery potential for new physics

- Dedicated reconstruction needed

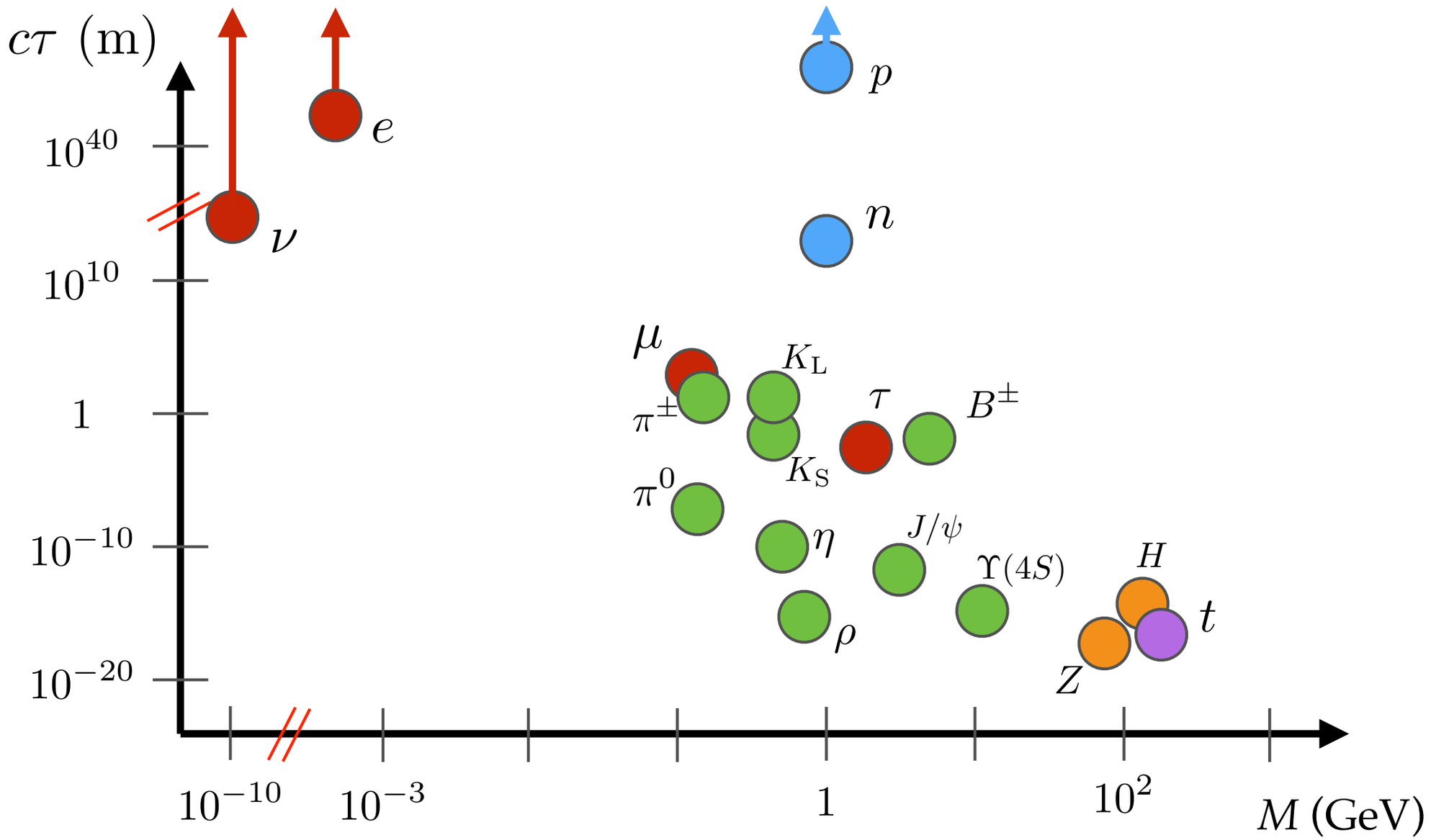
H. Russell



- Search methods specific to technologies deployed in detectors

LONG-LIVED PARTICLES

- Long-lived particles (LLPs) are theoretically well motivated:



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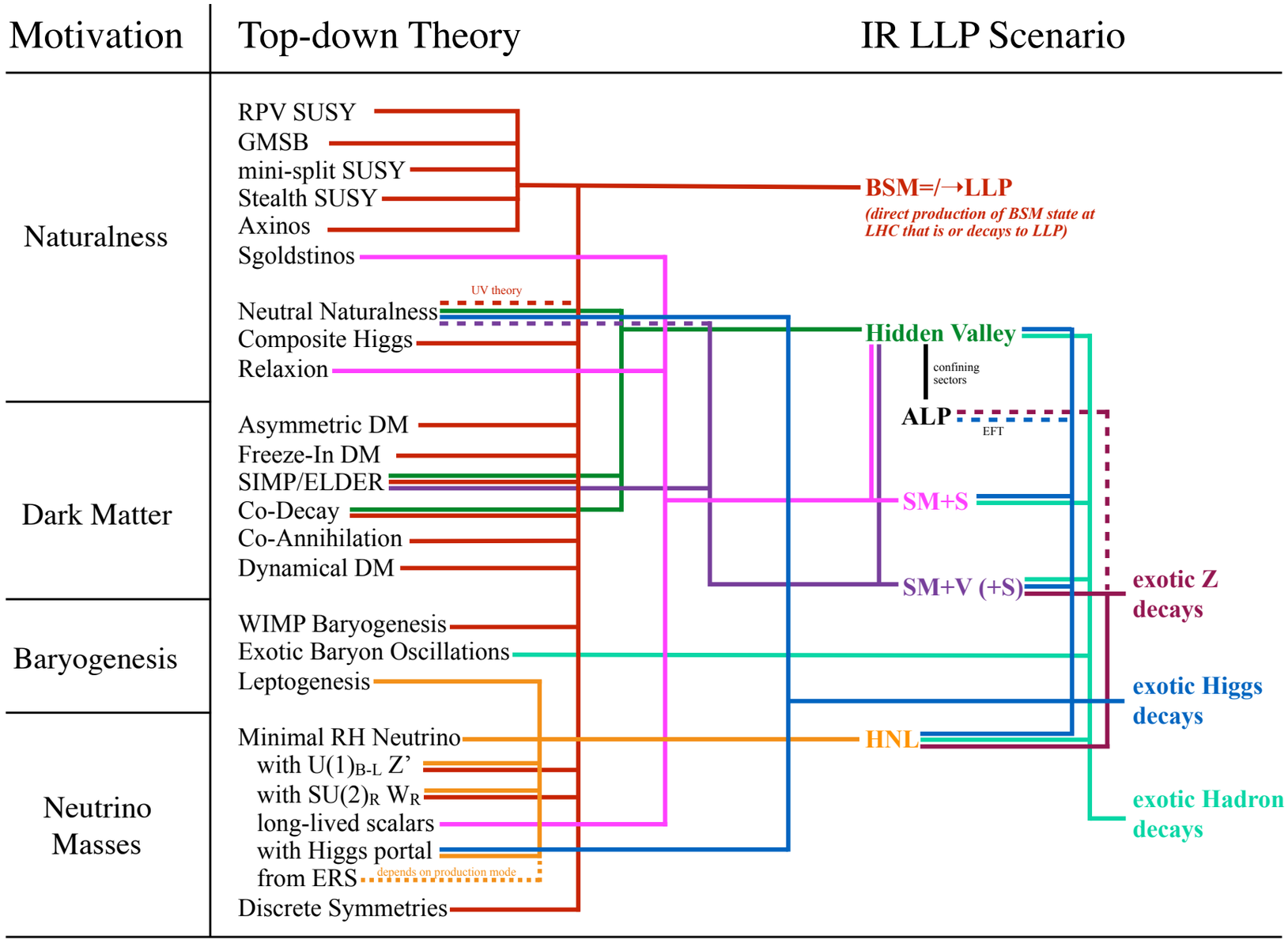

MOTIVATED SEARCHES

- How do we decide what is “most motivated” for LLPs?
  - Dark matter, neutrino masses, baryogenesis, naturalness give rise to LLPs over a huge range of masses, production rates, lifetimes, production modes, kinematic regimes, etc.
  - Very few of these models are contrived or reverse-engineered. LLPs seem to pop out whenever you think about one of these mechanisms

- Need broad and comprehensive search strategies to counteract small probability that any individual scenario is correct

HOW TO PRIORITIZE?

- #1 priority is to discover a new particle if it is out there!

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increasing priority

adjacent coverage

- Related search that is pretty effective
- Reinterpretation materials
- Most important for legacy results

sub-optimal coverage

- Related search with low efficiency

no coverage

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- Related search that is pretty effective
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- Most important for legacy results

sub-optimal coverage

- Related search with low efficiency
  - Does it pass any trigger?
  - Is it limited by background?
  - Is new technology needed?
  - The weirder the signature, the stronger the needed theory motivation

no coverage

see, *e.g.*, Chapters 3.6 and 7 of LHC LLP white paper, 1903.04497

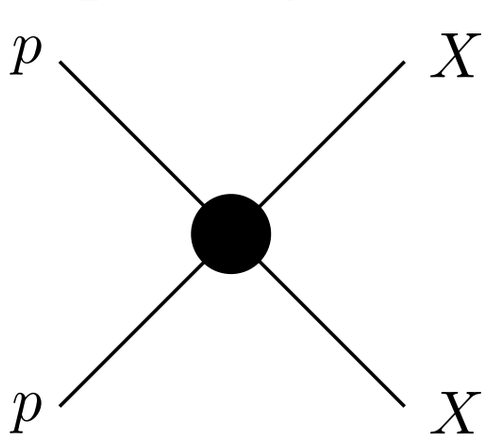
HIGH-PRIORITY SIGNALS

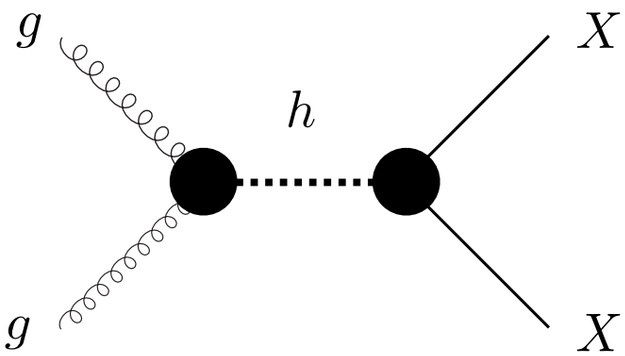
- **Some** examples of signatures with no or poor existing coverage:
    - Low-mass LLPs (especially hadronic, but also leptonic & semi-leptonic)
    - Decays with very soft leptons, hadrons (compressed spectra)
    - LLPs decaying to tau leptons
    - LLPs decaying to photons (unless accompanied by large MET)
    - Charged LLPs that decay on very short lengths (~mm)
    - Milli-charged LLPs
    - High multiplicities and/or strong dynamics in hidden sector
- May need to trigger on associated objects

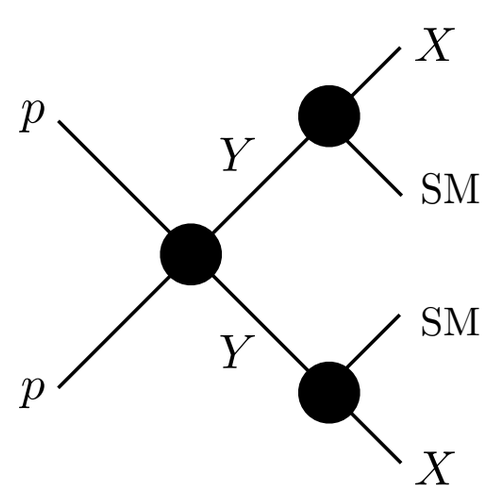
J. Beacham, G. Cottin, D. Curtin, J. Evans, Z. Liu, M. Ramsey-Musolf, J. Shelton, B. Shuve

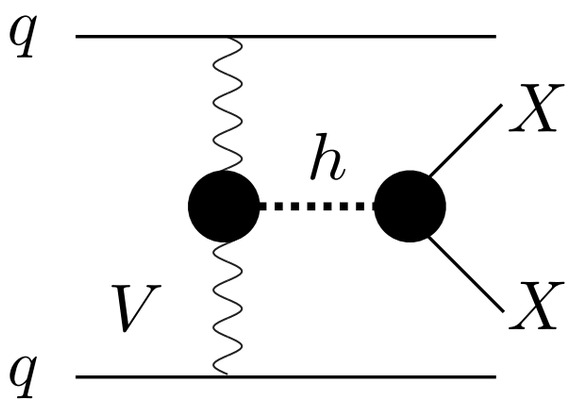
SIMPLIFIED MODELS

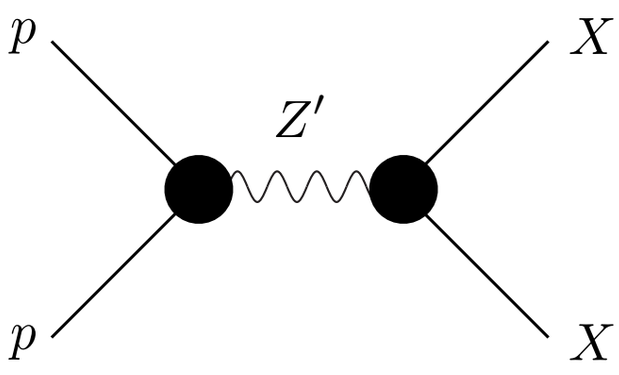
- The LHC LLP white paper has a fairly comprehensive set of simplified models for low multiplicity LLP signatures
- Factorize production and decay, goal is to span relevant kinematic ranges & particles produced in LLP decay (if any)

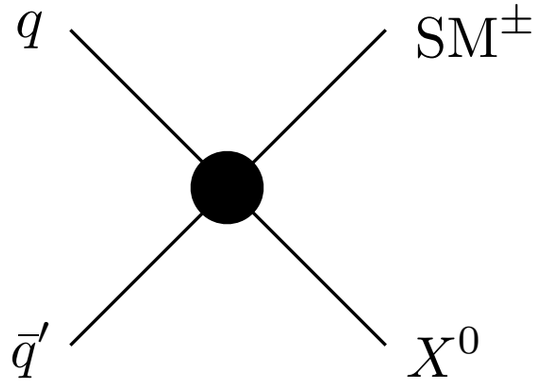












for more on simplified models, see Suchita's talk!

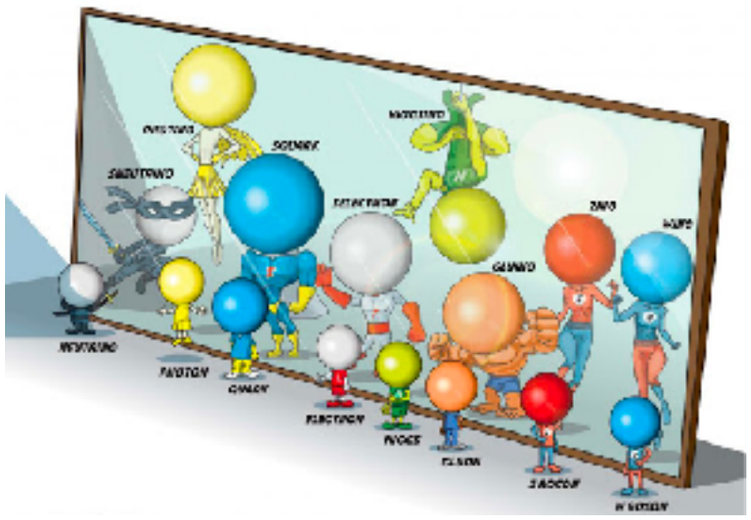
SIMPLIFIED MODELS

- Goal was to achieve broad coverage of signal, not optimized to specific spin, multiplicity (2 jets vs. 3 jets), etc.
- Example: neutral LLP

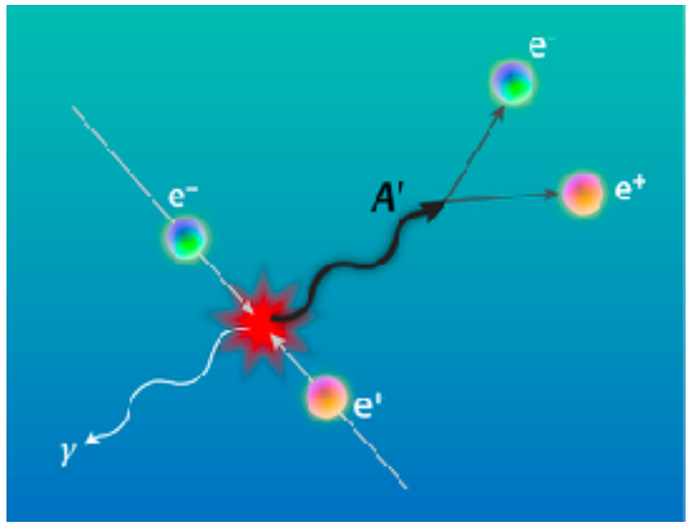
Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

BENCHMARKS

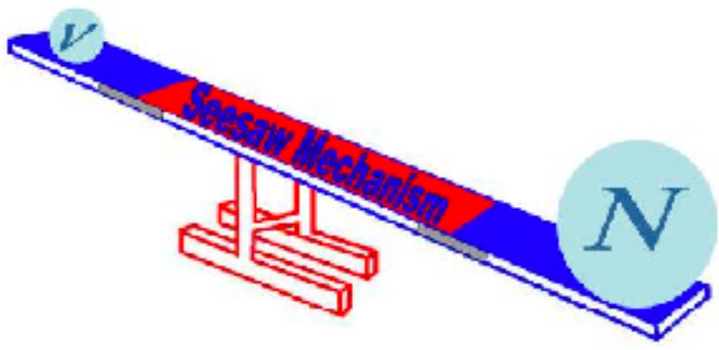
- Most of these signatures are covered by few complete models



supersymmetry (+RPV)

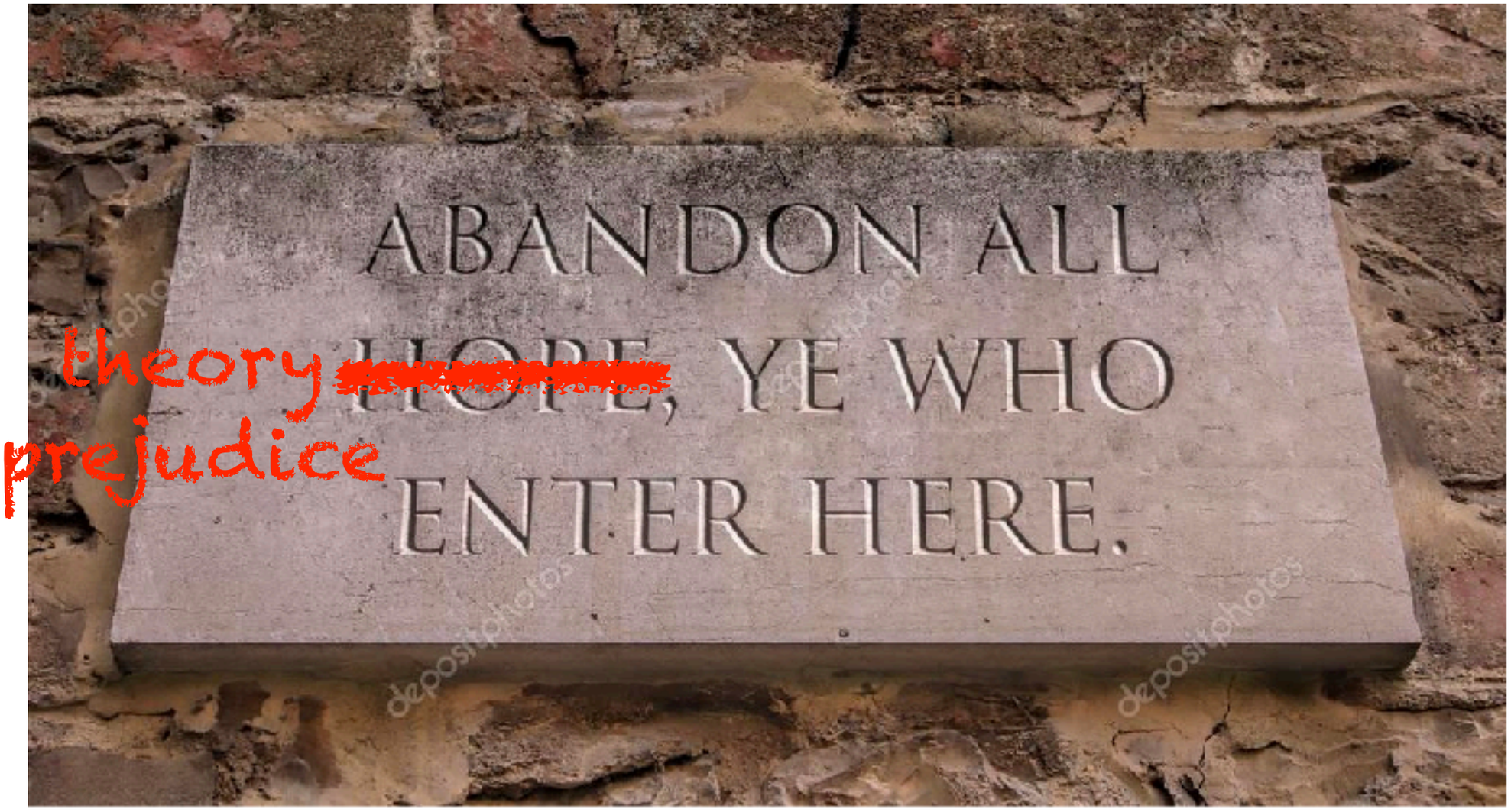


dark photons/Higgs (+ fermions)



type-I seesaw & extensions (e.g. LR symmetric model)

BENCHMARKS: CAUTION



- These are benchmarks and spectrum generators, meant for comparison of how we cover interesting signatures

see also *e.g.*,: L. Lee *et al.*, 1810.12602; J. Evans, J. Shelton, 1601.01326; F. Blekman *et al.*, 2007.03208

SUSY BENCHMARKS

- Great for higher-mass LLPs, strong & electroweak production, cascade decays

  Z. Liu, B. Tweedie, 1503.05923

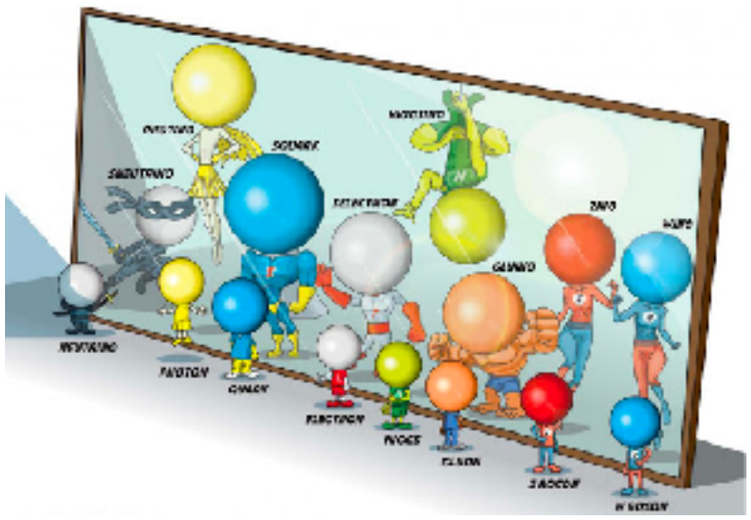
- Already many SUSY-inspired LLP searches, but should in principle look at all sparticle production times decay modes (incl. RPV)

- Beyond standard squark, gluino, electroweakino decay modes, some potentially interesting benchmarks to motivate new searches:

$$\tilde{\ell}_{\mathrm{R}} \to q\bar{q}' \text{ (RPV)}$$
$$\tilde{\tau}_{\mathrm{R}} \to \tau\tilde{\chi}_0$$
$$\tilde{\chi}^{\pm} \to \ell^{\pm}\tilde{\chi}^0 \text{ or } q\bar{q}'\tilde{\chi}^0 \text{ (compressed)}$$
$$\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0 \text{ or } \ell^+\ell^-\tilde{\chi}_1^0 \text{ (compressed)}$$
$$Z/h \to \tilde{\chi}^0\tilde{\chi}^0$$

BENCHMARKS

- Most of these basic signatures are found in a few complete models



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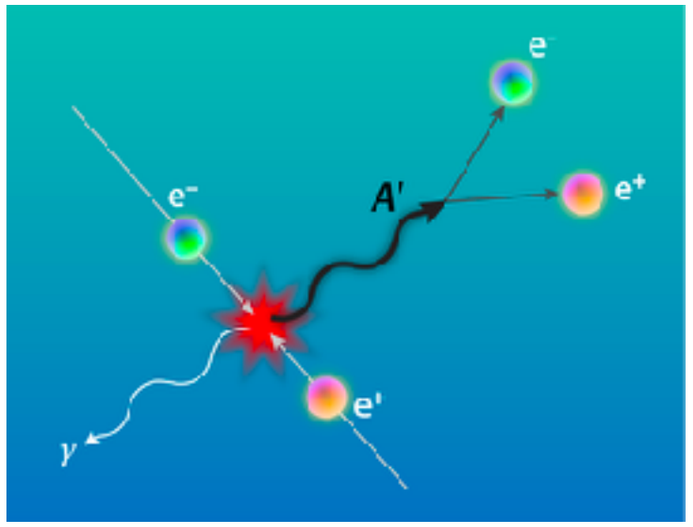

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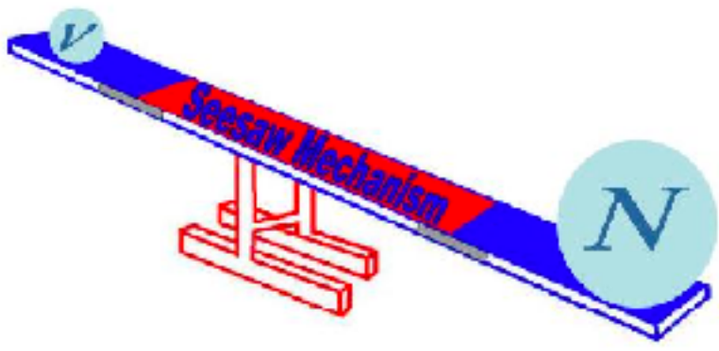


type-I seesaw & extensions (e.g. LR symmetric model)

DARK SECTOR BENCHMARKS

- We can take some cues from, *e.g.*, Physics Beyond Colliders report

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

  - Dark photon
  - Dark Higgs
  - Heavy neutral leptons
  - Axion-like particles
  - Milli-charged particles

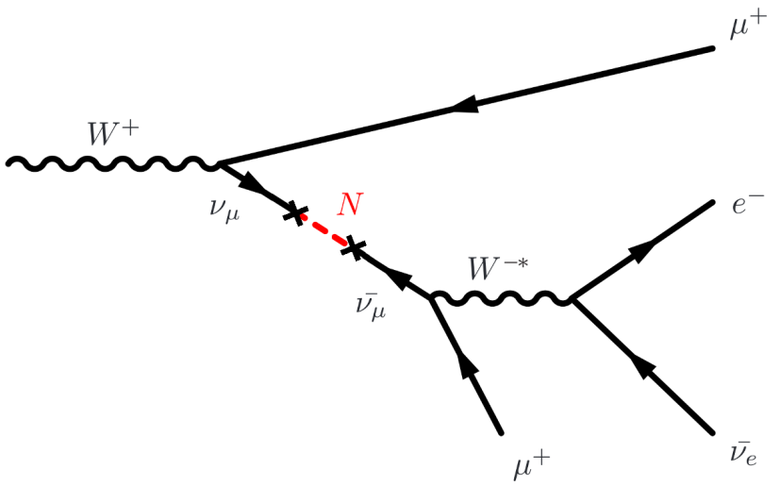
- Classic example: $h/h_{\rm d} \to XX,\ X \to b\bar{b}$ or $\ell^+\ell^-$

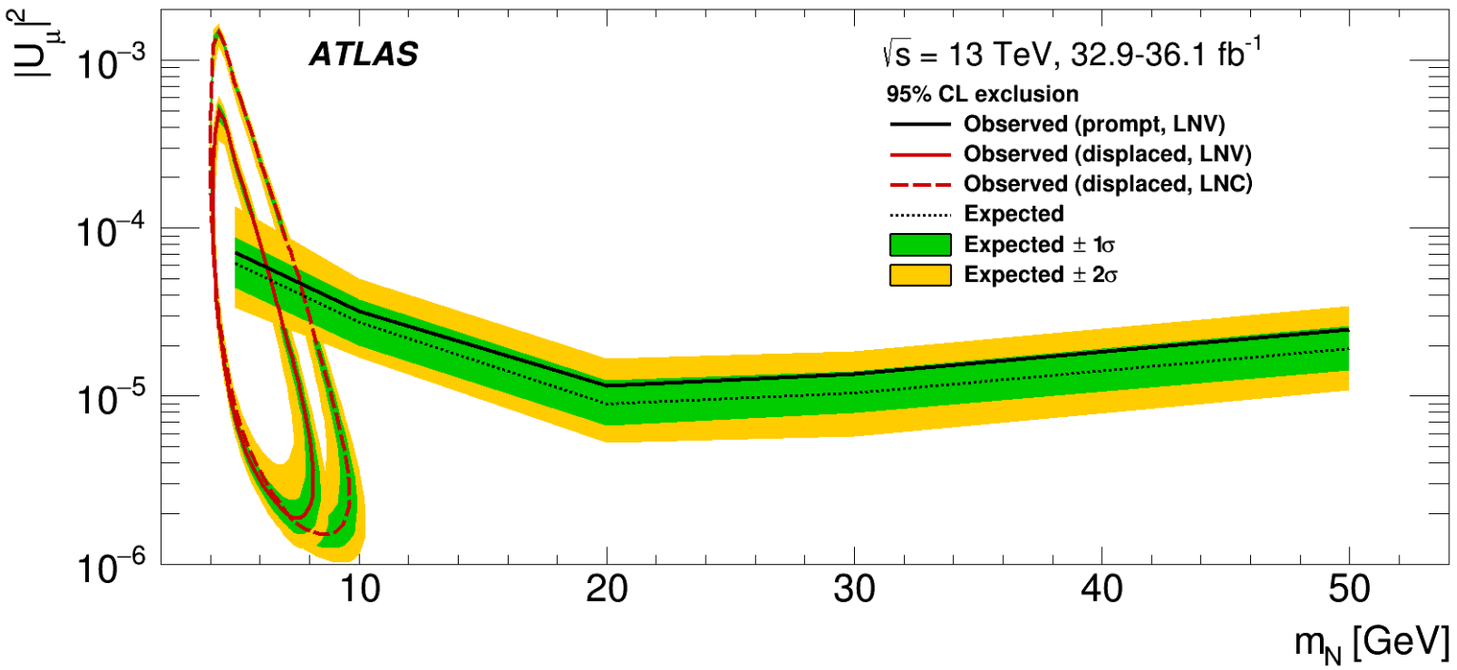
more on connection with Rare Frontier in a few slides

e.g., G. Cottin *et al.*, 1806.05191; J. Liu *et al.*, 1904.01020; K. Cheung *et al.*, 2004.11537, …

EXAMPLE: HEAVY NEUTRAL LEPTONS

- Major upswing in attention at EF in last couple of years!
- New ideas for discovering long-lived HNLs produced in *W*, Higgs, *B* meson decays
- First ATLAS displaced search (1905.09787) in trilepton signals:



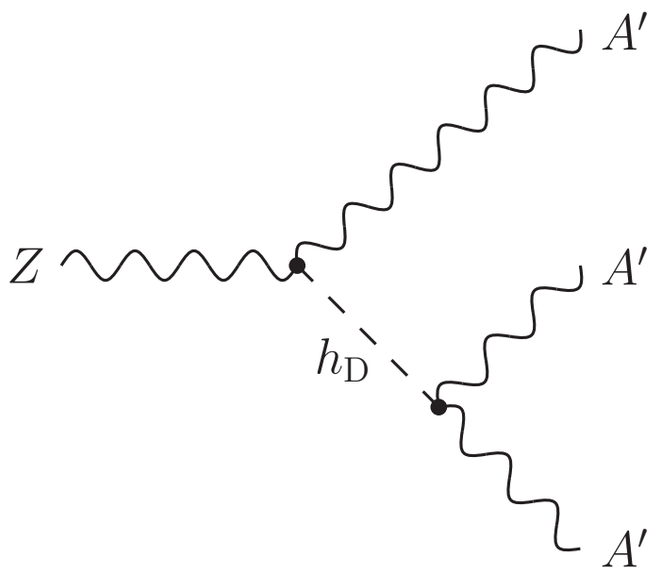


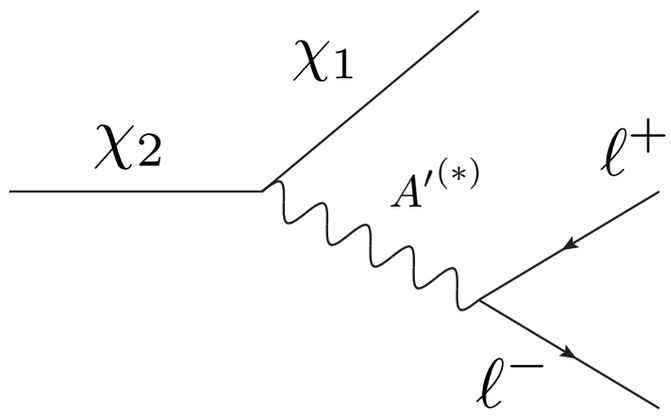
- HNL decay to tau leptons is a major gap

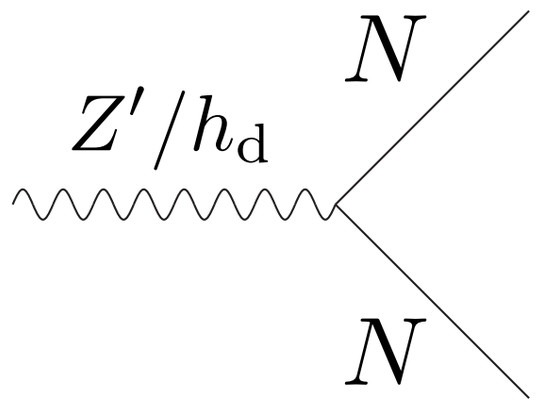
e.g., D. Curtin *et al.*, 1412.0018; E. Izaguirre *et* al., 1508.03050; B. Battell *et* al., 1604.06099; N. Blinov *et al.*, 1710.07635; E. Izaguirre, D. Stolarski, 1805.12136; A. Berlin, F. Kling, 1810.01879; G. Cottin *et al.*, 1806.05191

DARK SECTOR BENCHMARKS

- Are minimal models too simplistic?
- At low masses/energies, couplings are constrained to gauge-singlet portals, but at energy frontier can see large mass hierarchies, cascade decays, multiple portals…







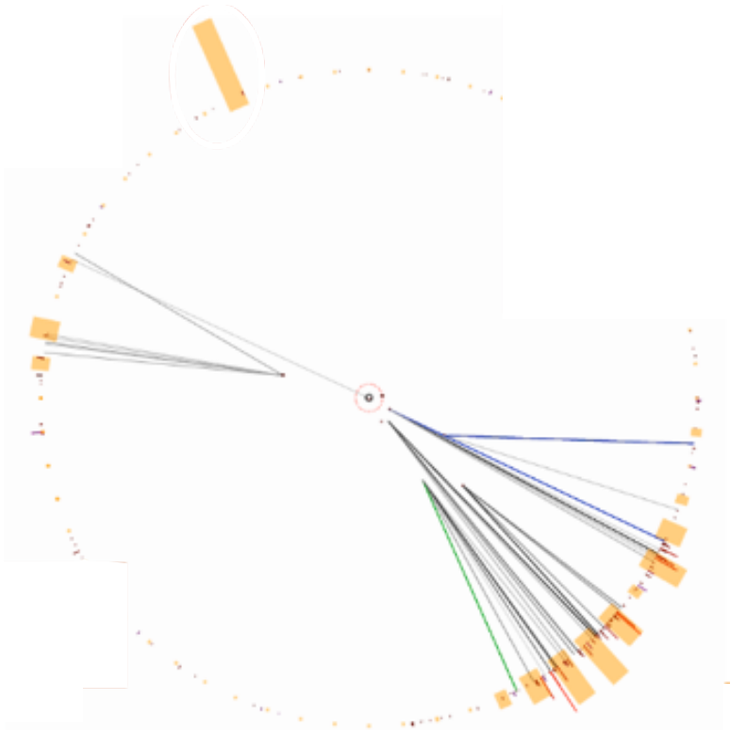
(or even $h \to 2h_{\rm d} \to 4A'$)

Strassler, Zurek, hep-ph/0604261; Strassler, Zurek, hep-ph/0605193; Strassler, hep-ph/0607160; Han *et al.*, 0712.2041

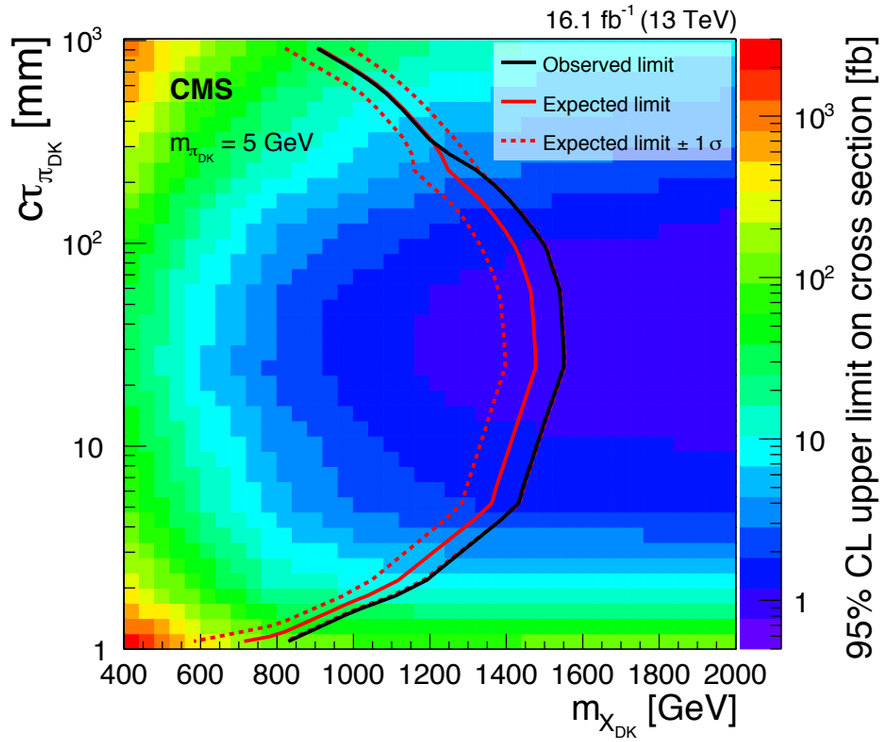
BEYOND MINIMAL: STRONG DYNAMICS

- The above frameworks completely fail for confining hidden sectors or other scenarios where we expect very high multiplicities
- First searches are being done, but this is very much in early stages!

direct search



P. Schwaller *et al.*, 1502.05409



CMS, 1810.10069

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inclusive search interpreted for dark shower

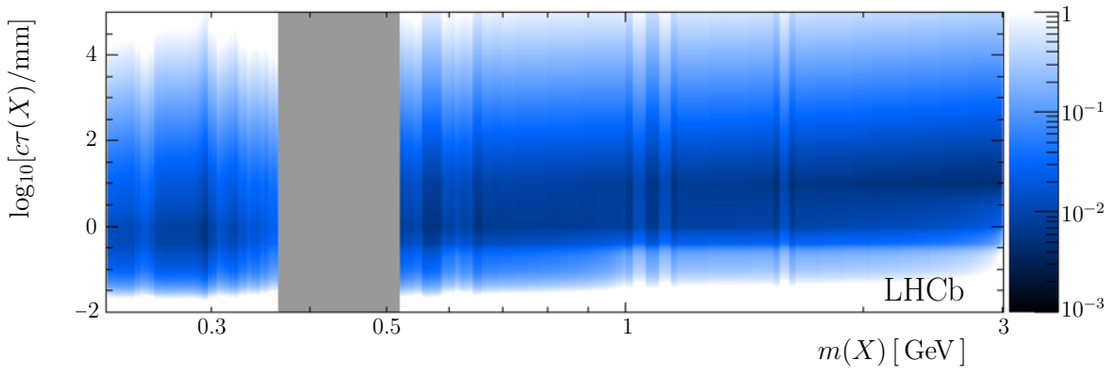
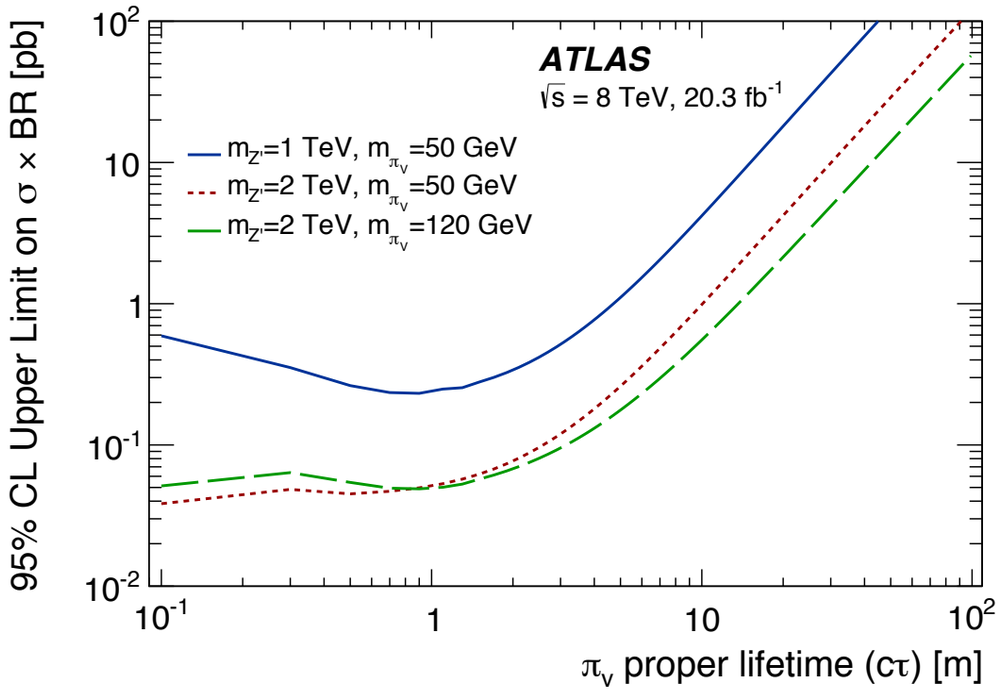


Figure 11: Upper limits at 90% confidence level on the γ–Z_{HV} kinetic mixing strength for the HV scenario discussed in the text.

LHCb, 2007.03923

A. Pierce *et al.*, 1708.05389



ATLAS, 1504.03634

see Chapter 7 of LHC LLP white paper, 1903.04497

BEYOND MINIMAL: STRONG DYNAMICS

- Existing searches assume confining dynamics resembles QCD
- For example, “soft bombs” or soft unclustered energy patterns (SUEP) give a more isotropic distribution instead of jets
- Factorize shower and hadronization for benchmarks:
  - QCD-like Yang-Mills theory
  - SUEP modelled with gauge theories at large ’t Hooft coupling
  - Phase space models that can generate isotropic distributions
  - Perturbative models with large-ish coupling
  - Wild extrapolations into intermediate regimes?
- White paper has excellent preliminary studies into whether this spans the full space of signatures, but more work needed!

see *e.g.*, M. Buschmann *et* al., 1505.07459; S. Knapen et al., 1612.00850; C. Cesarotti and J. Thaler, 2004.06125; T. Cohen *et al.*, 2004.00631

WHAT'S NEXT?

- If you are in a bit of a muddle…you are in good company. So am I, and many of us who work on LLPs!

- We have a task of identifying the most pressing signatures to explore, developing benchmarks to allow comparison of different strategies, and make proposals for the next 10 years

- Hopefully much of the work of the LHC LLP white paper and other similar studies can be used as a foundation to refine and clarify next steps

WE ARE NOT ALONE!

- Accelerator and rare process frontiers dealing with similar questions
- Recent joint meeting of EF9-10, RF6, AF5 (https://indico.fnal.gov/event/44030/). Check it out!
    - Main LHC experiments
    - External detectors (FASER, MATHUSLA, CODEX-b, etc)
    - Accelerator-based experiments & B-factories
- General agreement of success of PBC benchmarks at understanding complementarity of approaches, but also of their limitations
    - Strong desire to coordinate with high-energy experiments to bridge low-mass/high-mass gaps that might exists
    - Broaden range of signatures and models under study

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs.α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\ /\ \mu-\tau\ /\ B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→$\phi\phi$ ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	e/μ/τ a la1709.07001?	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasoanble flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* (separate?) Think more about reasoanble coupling relations including $f_{W/Z}$	FV axion couplings

\+ Neutron portal? Hidden valleys (or are these out-of-scope?)? See e.g. 2003.02270

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. Underline=CV benchmarks that were not used in BRN

Slide from: Brian Batell, Babette Dobrich, Stefania Gori, Phil Harris, Christopher Hearty, Phil Ilten, Gordan Krnjaic, Philip Schuster, Natalia Toro, Mike Williams, Jure Zupan

DISCUSSION QUESTIONS

- Some possible questions to discuss:
    - Of the uncovered signatures, which ones are most pressing in terms of new technologies or experiments needed? Which ones are do-able but need more person-power or resources?
    - Are there broad classes of signatures and/or theory models that are not covered?
    - With such a broad range of possible signals and models, how do we organize, prioritize, and compare future approaches?
    - What are the most outstanding questions that need to be addressed for LLPs at future colliders vs. the LHC?
    - Best benchmarks for low-mass LLPs, connections with intensity frontier?